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The Japanese Nuclear Fusion Program

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An Intelligence Assessment

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March 1985*

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An Intelligence Assessment

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queries are welcome and may be directed to the
Chief, Nuclear Energy Division, OSWR []

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**The Japanese Nuclear
Fusion Program**

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Key Judgments

*Information available
as of 28 January 1985
was used in this report.*

The Japanese Government made Japan's nuclear fusion research program a top-priority national research project in 1975. Support for this program has continued because the Japanese believe that fusion is the most promising energy source for the future and will contribute to the solution of Japan's future energy problems. We believe that the Japanese nuclear fusion program is solely a civilian program for developing a new energy source.

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The Japanese fusion program is well organized, comprehensive, and broad based. After a decade of rapid progress to an overall position second only to that of the United States, the pace of the program is slowing naturally as the Japanese approach the limits of proven technology. We expect that the program will continue to make steady progress and will make major contributions to international fusion research.

The Japanese fusion program emphasizes the tokamak approach in which a plasma is magnetically confined in a doughnut-shaped vessel. Barring unexpected technical difficulties or significant advances in other approaches, it will continue to do so in the foreseeable future. The earliest date that Japan could have a demonstration fusion power reactor operational would be about 2010.

Because of the large sizes and costs of future fusion projects, we believe the Japanese will continue to stress international projects and probably will be receptive to any Western initiative for a joint program to build the next large tokamak. Even with extensive international cooperation, a demonstration fusion power reactor would not be likely before about 2005.

Japanese industry is actively involved in the fusion program and is positioning itself to take advantage of future markets for fusion devices or fusion-relevant equipment.

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The Japanese Nuclear Fusion Program

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Background¹

Nuclear fusion is a combustion process that produces thermal energy that can be used to generate electricity. As an energy source, nuclear fusion has several advantages over other energy sources such as oil, coal, and nuclear fission. Fusion fuel (see appendix) can be extracted from seawater in an environmentally benign way. There appears to be practically no limit to the amount of fusion fuel that can be extracted at a relatively cheap cost. In addition, a fusion power reactor will produce far less radioactive waste than a fission power reactor. []

The complexities of developing a fusion power reactor center around the need for very high temperatures. (See the appendix for explanations of the requirements of nuclear fusion and for descriptions of the confinement schemes being developed.) Although major advances have been made during the last 30 years in the areas of heating and containing hot fusion fuel, significant engineering problems in areas such as materials, superconducting magnets, and reactor design still need to be addressed. In the view of many fusion specialists, it will most likely be at least 40 years before a utility power plant generates electricity using nuclear fusion. The actual time will be very dependent on the funding provided for worldwide fusion programs and on the rate of scientific/engineering advances. []

By use of a concept known as the fusion-fission hybrid reactor (see appendix), fusion also can be used to breed fissile fuel, particularly for fission reactors. Calculations indicate that the hybrid reactor probably would be a very efficient breeder reactor. The addition of a fission blanket around a fusion reactor, however, creates numerous engineering and materials problems that have not been adequately addressed. This application will remain only an interesting potentiality until one or more countries initiate serious developmental programs. []

¹ Our analysis is based on information on nuclear fusion found in worldwide open literature []

The origins of the Japanese fusion program were small-scale experiments undertaken at several universities in the mid-1950s. The Japanese established the Institute of Plasma Physics at Nagoya University as a center for fusion research in 1961. At that time, Japanese fusion scientists, and their counterparts in the rest of the world, were quite optimistic about the near-term promise of fusion energy. As a result, Japanese industry became deeply involved in fusion research and development. By 1968, however, it became evident that a fusion program would be a lengthy, high-risk, and large-scale undertaking. Thus, the Japanese Government assumed responsibility for the fusion program; in 1975, the government made the fusion program a top-priority national research project. []

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The Japanese have continued to support nuclear fusion research because they believe it is the most promising energy source for the future. Because of a lack of energy supplies and natural resources, the Japanese have promoted scientific technology and stressed the necessity of scientific research and development. They believe that nuclear fusion research will accelerate the development of support technologies and will contribute to the solution of their country's future energy problems. []

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The Japanese fusion program is comprehensive and broad based. A list of the major approaches to fusion being followed in Japan is given in the table. Also listed in the table are the primary institutes investigating each approach. The strengths of the Japanese program are in the areas of tokamak, magnetic mirror, stellarator, and laser fusion experimental devices. In addition to their device-related programs, the Japanese have programs to develop most of the technologies relevant to the development and construction of a fusion power reactor. []

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**Major Fusion Approaches
and Primary Institutes**

Approach	Institutes ^a
Tokamak	Japan Atomic Energy Research Institute Nagoya University Tokyo University Kyoto University Kyushu University Hitachi
Stellarator	Kyoto University Nagoya University Tohoku University
Magnetic mirrors	Tsukuba University Nagoya University Kyoto University Kyushu University
Pinches	Electrotechnical Laboratory Nagoya University Nihon University Tokyo Institute of Technology
Ion/electron rings	Osaka City University Nagoya University
Bumpy torus	Nagoya University
Laser fusion	Osaka University Electrotechnical Laboratory Keio University Nagoya University
Particle-beam fusion	Osaka University Tokyo Institute of Technology Nagaoka Technical University

^a The first institute listed is the lead laboratory for the approach.

The major components of the Japanese fusion program and their interconnections are shown in figure 1. Fusion research and development are funded and carried out under the jurisdiction of three governmental ministries: the Science and Technology Agency (STA), the Ministry of International Trade and Industry (MITI), and the Ministry of Education, Science and Culture (MOE). The Atomic Energy Commission (AEC) serves as the policymaking body for all nuclear energy development programs in Japan. The Nuclear Fusion Council (NFC) of the AEC draws up the basic national policies for fusion research and development, coordinates the programs of the three ministries, and reviews the performance and promise of the programs.

The Japan Atomic Energy Research Institute (JAERI) was established under the STA in 1956 for the purpose of developing and utilizing nuclear energy in Japan. The JAERI is now responsible for developing the tokamak into a viable fusion reactor. The universities, under the MOE, are responsible for the research and development of nontokamak approaches to fusion and for the basic plasma physics research needed to develop fusion. The Science Council of the MOE is responsible for formulating the basic policies for the fusion research conducted in the universities. The Committee on Nuclear Fusion was established in 1980 by the Japan Atomic Industrial Forum to formulate the role of industry in the national fusion program.

Fusion Research Programs

We cannot accurately estimate the size of the Japanese fusion budget because quoted budgets are only for device construction. To get an accurate budget estimate, we would need to know the personnel and administrative costs, developmental costs borne by industry, cost overruns on equipment construction absorbed by industry, and costs of bilateral cooperation programs. From the quoted budgets, however, we can perceive trends and growth rates.

The Japanese fusion effort is highly skewed toward tokamak research. For Japanese fiscal year 1981, we estimate that roughly 80 percent of the total fusion budget of over \$250 million was devoted to tokamaks—a situation also evident in the fusion budgets of Western Europe and the USSR. By comparison, the United States devoted about 30 percent of its total FY 1981 fusion budget of \$595 million to tokamak-related research.

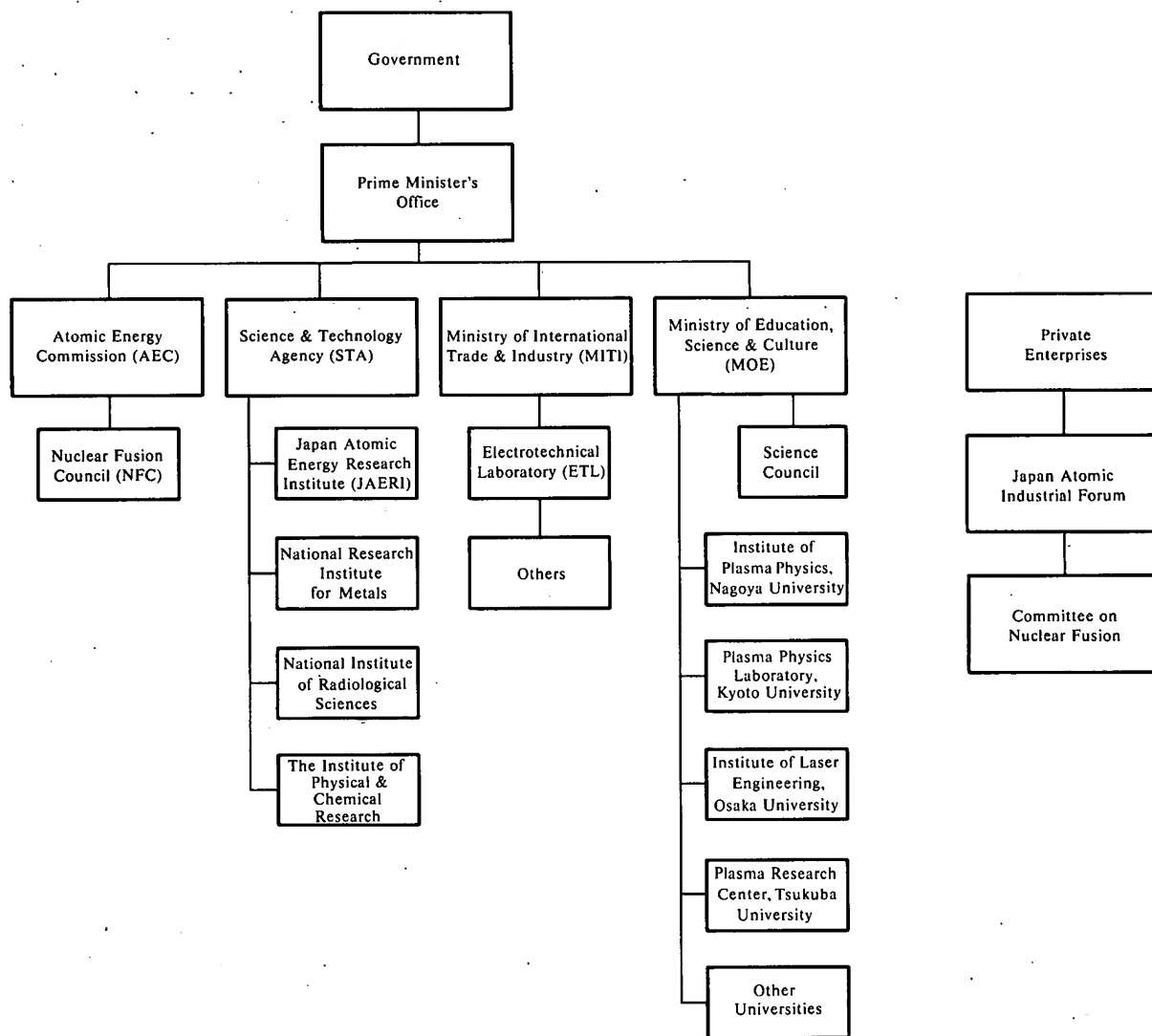
we estimate that the Japanese devote about 40 percent of their total nuclear research and development budget to fusion. The Japanese national fusion budget leveled off for the first time in FY 1983.

The dominance of the tokamak in the Japanese fusion program is also evident in existing long-range plans.

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Figure 1
Organization of Fusion Research in Japan



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The nuclear energy program put forth in 1978 called for the construction of two fusion devices after the completion of the JT-60 tokamak in 1985. The Japanese assumed that these devices, which were to be used to prove out tritium technology, would be tokamaks. As a result of the rapid progress that had been made worldwide on tokamak research, the Japanese formally revised their long-range program in 1982. The program now calls for the Japanese to proceed directly from the JT-60 to a tokamak device capable of demonstrating engineering feasibility (defined in appendix). This device, known as the Fusion Experimental Reactor (FER), combines the objectives of the two devices called for in the 1978 program. []

The Japanese realize that the tokamak potentially has some serious problems that could make it unsuitable for development into a practical fusion reactor; the potential problems stem from the fact that currently the tokamak has a complex configuration and is a pulsed machine. For this reason, the 1982 program calls for the universities to continue fundamental fusion research and the development of nontokamak alternatives. The work on these alternative approaches is to proceed to the point of demonstrating scientific feasibility (defined in appendix). []

Although it is an established principle of Japan's long-range program for fusion to develop the relevant technologies indigenously, it is also an established principle to encourage international cooperation. The stated goal of this cooperation is to accelerate effectively the relevant fusion activities of each country in ways that are consistent with the programs of each country. []

The largest, and most important, Japanese cooperative program is with the United States. The program, which was formalized in 1979, includes workshops, exchange visits, and joint projects. The largest of the joint projects is that using the Doublet III tokamak in California. In 1979 the Japanese agreed to provide over \$60 million for the upgrading and operation of the Doublet III for a five-year period. In return for this support, the Japanese were given half of the experimental time on the tokamak. In 1983 the Doublet III agreement was extended until 1988. In

the future, the Japanese financial support will be used to pay for reconfiguring the tokamak and attempts will be made to operate the Japanese and American scientific teams as a joint research team. []

Japan's approach to its fusion program, and the tokamak program in particular, is a holistic one. The Japanese have developed a list of the technologies needed for the development of a fusion reactor and have set about developing each technology separately. Meanwhile, they are also developing different types of fusion devices without incorporating advanced technologies before they are sufficiently developed or when their use unduly complicates the operation of the device. In addition, they consider their work on foreign devices, such as the Doublet III, as an integral part of their program. The final integration of all these pieces will occur when the technologies are fully developed and an optimum design can be determined. []

Tokamak Program

As part of its program to develop a tokamak fusion reactor, JAERI has developed a number of facilities to advance technologies considered crucial to the development of a fusion reactor (for example, neutral beams, superconducting magnets, and tritium handling). Currently, the premier technical device of this program is the JT-60 tokamak (see figure 2 for a schematic), which is to become operational in early 1985. The JT-60 will be comparable and complementary to the world's two state-of-the-art tokamaks. These tokamaks are in the United States and the United Kingdom; they became operational in 1983. []

As the follow-on to the JT-60, JAERI is designing the FER (see figure 3 for schematics of a US design similar to the FER). The goals for the FER are to demonstrate engineering feasibility and provide operation experience with many of the technologies needed for a fusion reactor. []

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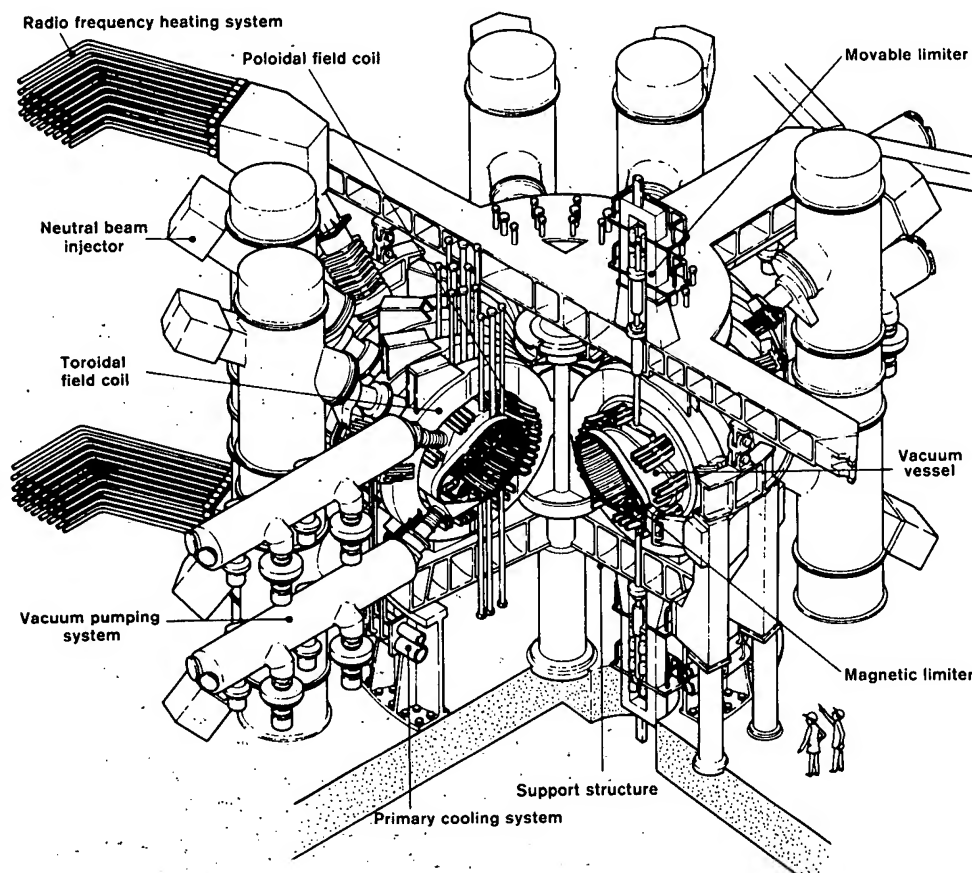
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Figure 2
Japanese JT-60 Tokamak



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physics issues. Much of this effort is centered at the Institute of Plasma Physics (IPP) of Nagoya University.

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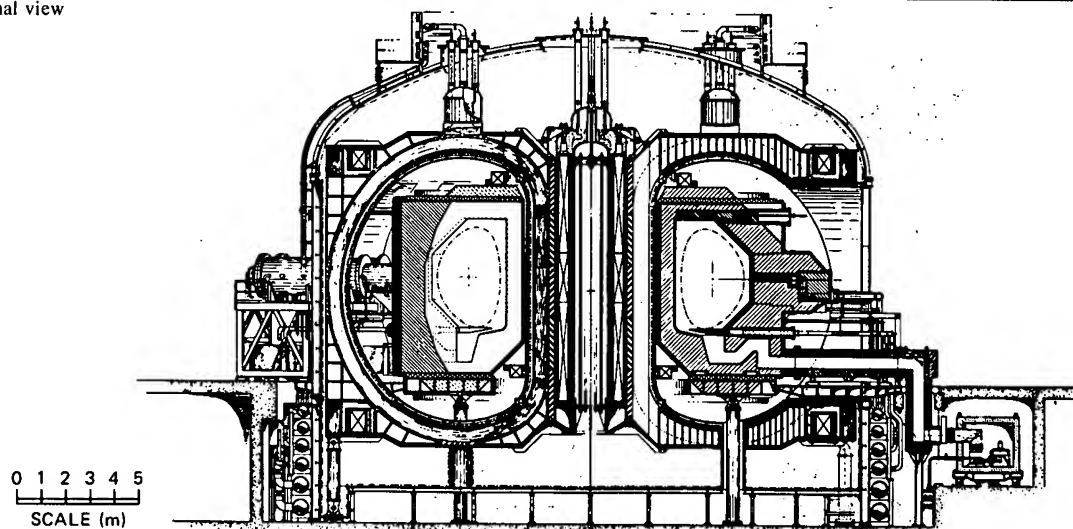
The role of the universities in the tokamak program is to educate and train scientists and to research basic

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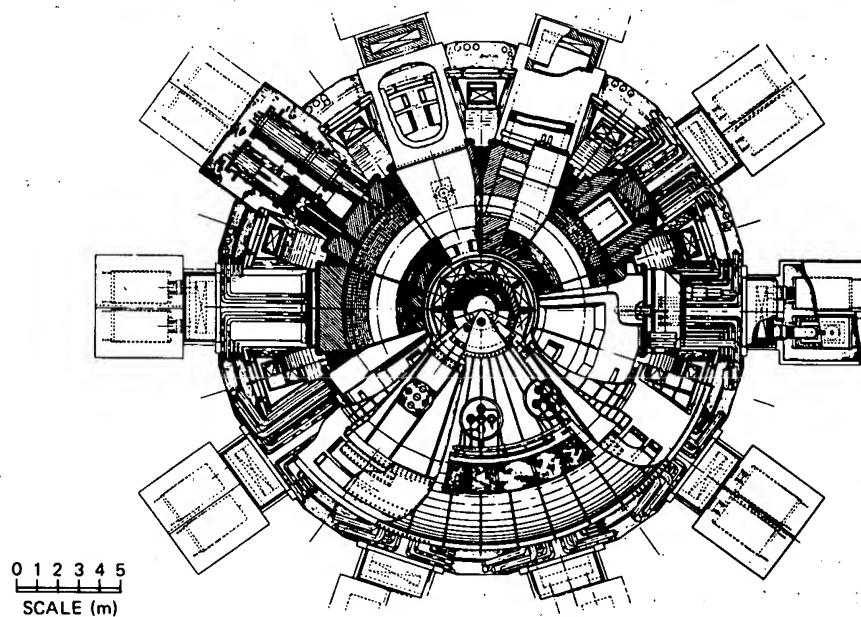
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Figure 3
US Tokamak Design Similar to
Japanese Fusion Experimental Reactor

Cross-sectional view



Top view



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Nontokamak Approaches

Stellarator. A number of stellarator-type devices known as heliotrons have been developed at Kyoto University. The latest of these devices, the Heliotron E, became operational in 1981. The only other stellarator in the world comparable to it is in West Germany.

Magnetic Mirror. The primary Japanese magnetic mirror research program is the Gamma series of experiments. This program, which began with simple linear mirror devices, is 10 years old and is located at the University of Tsukuba. After scientists in the United States and the Soviet Union put forth the concept of a tandem magnetic mirror device during

1976-77, the Japanese quickly built the small Gamma 6 device. This device, which demonstrated enhanced plasma confinement in 1978, was the first operating tandem magnetic mirror device in the world. The first plasma was obtained in the larger Gamma 10 tandem mirror device in 1982. This will remain one of the two premier tandem mirror devices in the world (the other is the Tandem Mirror Experiment-Upgrade in the United States) until a larger one becomes operational in the United States in 1986.

Laser Fusion. The Institute of Laser Engineering (ILE) at the Osaka University is the lead laboratory for laser fusion research in Japan. In 1980 the ILE undertook Project Kongoh, which has the goal of demonstrating scientific feasibility before 1990. The initial phase of this program is centered around the Gekko XII glass laser, which became fully operational in late 1983. This was a world-class fusion laser until

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the United States completed its NOVA laser system in late 1984. As the culmination of Project Kongoh, the Japanese plan to complete a NOVA-size (about 100 kilojoules) laser system in the late 1980s; developmental work for this laser is now under way. As part of Project Kongoh, the Japanese are now completing the development of target irradiation and target fabrication facilities. []

the equipment the Japanese produce is generally on a par with similar US equipment and, in many cases, is superior in its engineering and operation. Not only has the Japanese fusion program been supplied with superbly designed and constructed equipment, but also the Japanese industries have put themselves in a good position to take advantage of future domestic and foreign markets for fusion devices or fusion-related equipment. []

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Fusion and Nuclear Proliferation

During the last several decades, there have been varying levels of concern about the relationship between nuclear power programs and nuclear proliferation. Originally, this concern centered around fission reactors and their capability to produce fissile material that could be used in nuclear weapons. Later, nuclear fusion research came under scrutiny because of its potential for producing fissile material and because of the physics involved. []

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Industrial Involvement

Japanese companies have been involved in fusion research since the early days of the program—Hitachi built a linear magnetic mirror device in 1960. This involvement stemmed not only from the initial optimism about fusion but also from the fact that, traditionally, Japanese universities and national research organizations have not built adequate machine shops. As a result, research equipment has generally been manufactured by private industrial companies. []

All fusion reactors using the deuterium-tritium reaction produce tritium, which also could be used in nuclear weapons. The principal concern from the standpoint of fissile material production, however, is the fusion-fission hybrid reactor (see appendix). []

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The long-range viewpoints of Japanese companies have led to many major contributions to the national fusion program. The companies have been willing to develop one-of-a-kind pieces of materials and equipment; and they have often undertaken such development with their own corporate funds. In addition, they have regularly stationed personnel at institutes such as JAERI for training and interaction with fusion physicists. []

The physics of inertial confinement fusion techniques such as laser fusion (see appendix) is similar in some respects to that of nuclear weapons. In both cases, matter is compressed to very high densities and contained for very short periods (nanoseconds) before it explodes. The imploding system for laser fusion, however, is smaller in size by a factor of 100,000 and operates at lower temperatures and pressures than does a nuclear weapon. In addition, much of the

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Japanese companies have proved to be quite capable of adopting and improving Western fusion-related technology. In the opinion of many Western scientists,

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implosion physics is masked by laser-plasma interactions. [REDACTED]

[REDACTED] The primary utility of such research would be in the training of scientists and the generation of ideas. [REDACTED]

We believe that the Japanese will continue to emphasize international cooperation and joint fusion projects to maximize their resources and progress. The most likely large joint project to be undertaken is a large tokamak similar to the Japanese FER design. For such a project, the other participants would be the United States and/or the European Economic Community or possibly only West Germany. [REDACTED]

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If the Japanese cannot reach an international agreement to build the next large tokamak, we believe that they will build the FER. Whether the construction of the FER is undertaken in this decade will depend on budgeting, worldwide progress on tokamak research, and the worldwide economic climate. If they are forced to go it alone and do not encounter any severe financial or technical difficulties, we expect the Japanese to proceed steadily and to build a demonstration fusion power reactor. Assuming the best economic and scientific/engineering conditions, it is unlikely that such a reactor will be operational before about 2010. An intensive, coordinated international cooperation program would include the sharing of the development of auxiliary technologies and could reduce this timetable by about five years. [REDACTED]

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Future

We believe that overall the Japanese fusion program lags only the fusion program in the United States. During the next five years, the Japanese probably will be major contributors to research in the tokamak and stellarator areas. They could also make significant contributions to laser fusion and magnetic mirror research. We believe that the Japanese fusion program will continue to emphasize the tokamak approach. This emphasis will only be modified if worldwide tokamak experiments reveal some unexpected technical difficulties and other experiments demonstrate that another approach is as attractive as the tokamak appears today. [REDACTED]

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The Japanese have made rapid progress in their fusion program during the last decade. We believe that this rate of progress will decline naturally in the future as the Japanese approach or reach the frontier level in many fusion-related technologies. In addition, future fusion projects will of necessity be very large and costly. [REDACTED]

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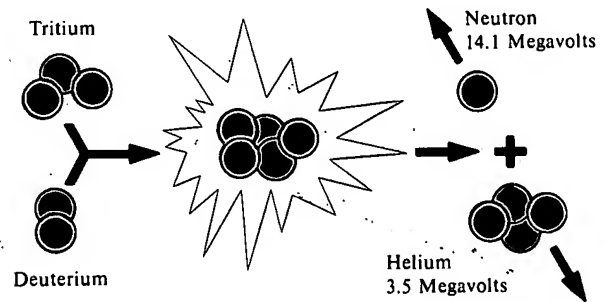
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Appendix

Nuclear Fusion Concepts

Nuclear fusion is a nuclear process in which two light nuclei fuse together, react, and release energy. The most useful fusion reactions are those between nuclei of deuterium and between nuclei of deuterium and tritium; deuterium and tritium are heavy isotopes of hydrogen. The first fusion power reactor will use the deuterium-tritium (D-T) reaction (figure 5). Because tritium is radioactive and requires special production and handling, it is desirable that ultimately fusion power reactors will use the deuterium-deuterium reaction. Deuterium is a naturally occurring hydrogen isotope that can be extracted from seawater.

Figure 5
The D-T Fusion Process



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In the deuterium-tritium (D-T) fusion process, a deuterium nucleus (which consists of one neutron and one proton) fuses with a tritium nucleus (which consists of one proton and two neutrons). The two protons and two of the neutrons combine to form a stable helium nucleus (also known as an alpha particle); the other neutron escapes with 80 percent of the released energy in the form of kinetic energy.

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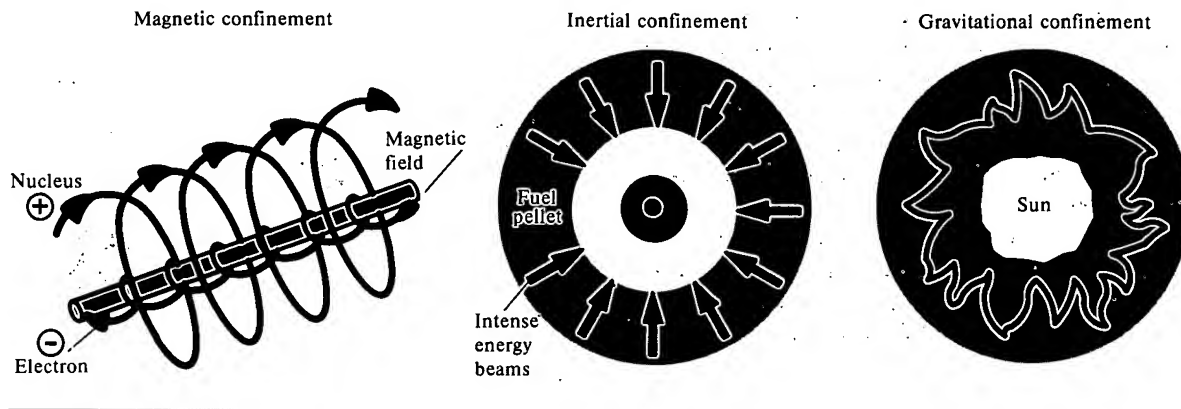
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Figure 6
Types of Plasma Confinement



There are three ways to contain a hot plasma in which fusion reactions are occurring. Magnetic confinement is based on containing a low-density, high-temperature plasma for several seconds while the fusion reactions proceed. Inertial confinement occurs when a fuel pellet is compressed to high density and temperature by intense nanosecond-long energy beams. Gravitational confinement takes place in the stars and uses their enormous masses to compress and heat light elements to fusion conditions.

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Nuclei naturally repel each other because of their like electrical charges. Energy must be added to a gas of fusion fuel to increase the probability of collisions between the nuclei. The resulting high-temperature gas, which consists of nuclei and electrons, is called a plasma. In a fusion power reactor, the plasma will have a temperature exceeding the core temperature of the sun (over 10 million degrees). Thus, special techniques must be developed and employed to contain the

fusion plasma and maintain its high temperature. Three types of plasma containment are feasible: magnetic, inertial, and gravitational (figure 6). The third type is only feasible in the stars and is not relevant to terrestrial research.

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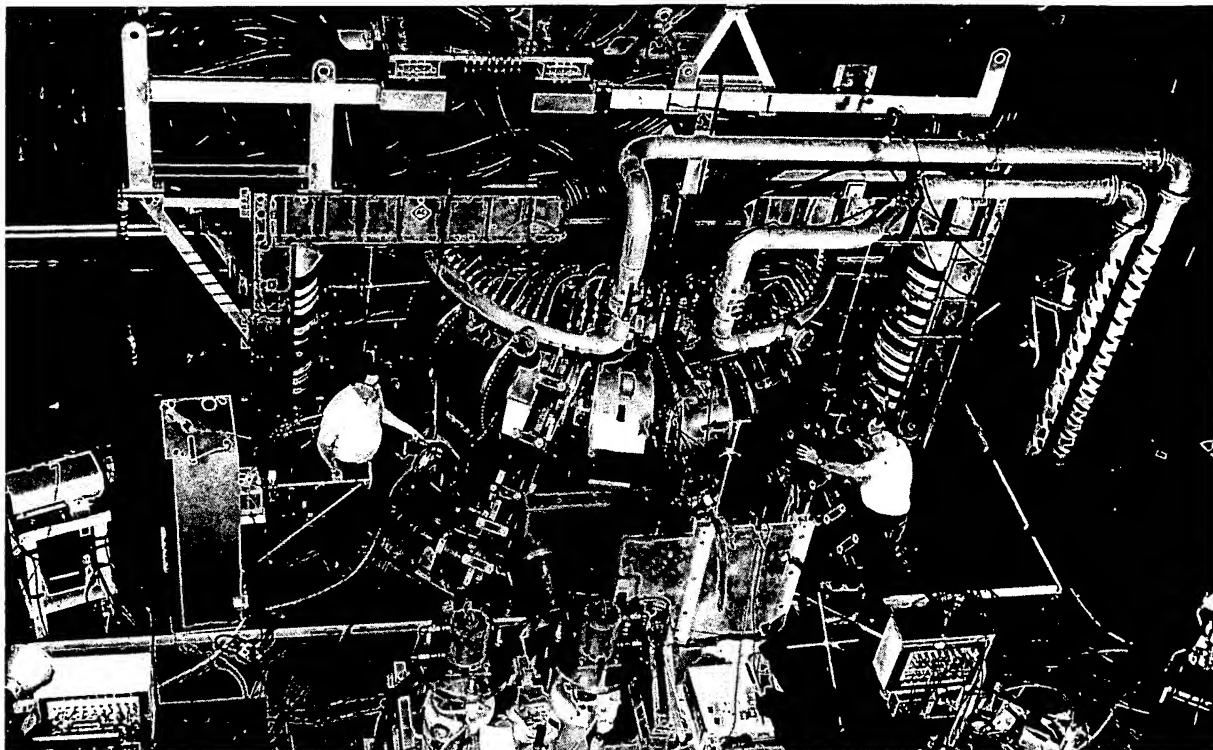
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Figure 7
US Tokamak Operated in the 1970s



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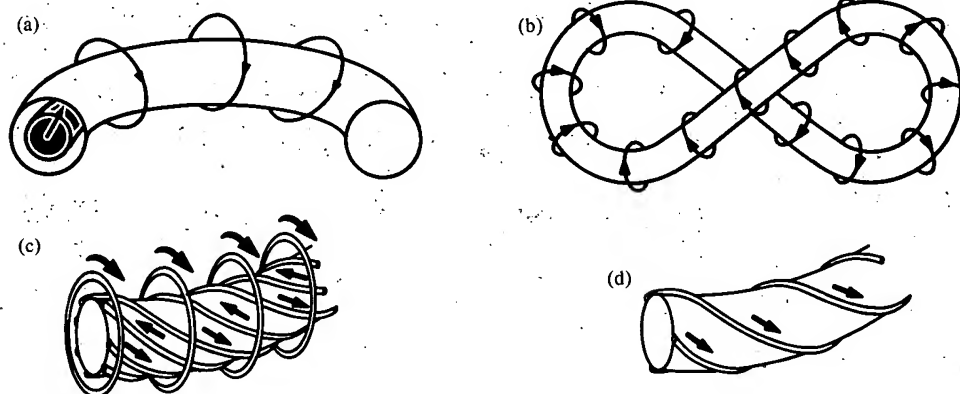
Magnetic confinement fusion (MCF) is based on the fact that charged particles spiral around magnetic field lines (figure 6). The various MCF devices that have been developed represent different ways of creating magnetic fields for stably containing the plasma. Currently, the most prominent MCF devices are the tokamak, stellarator, and magnetic mirror. Other types of MCF devices that are being used are the

magnetic pinch, the bumpy torus, ion rings, and electron rings. The tokamak (see figures 2 and 3 and the photograph in figure 7) is the MCF device on which the most effort has been expended; consequently, it is currently the most developed fusion device and likely will be the device on which the first fusion reactor is based.

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Figure 8
Types of Toroidal Magnetic Confinement Fusion Devices



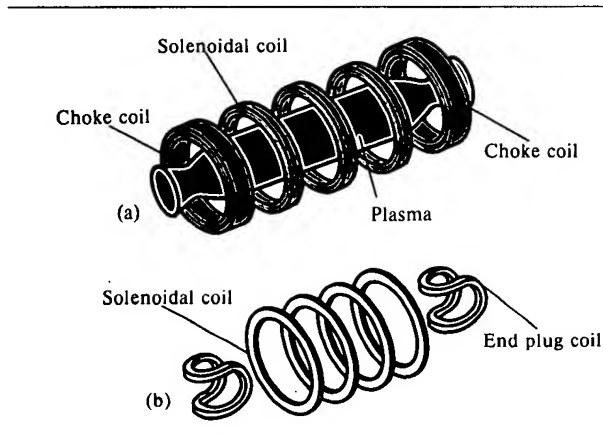
(a) In the tokamak, the main toroidal magnetic field is provided by poloidal coils. The poloidal magnetic field is created by a toroidal current in the plasma. Several external toroidal coils (not shown in the sketch) provide a vertical magnetic field and drive the plasma current. (b) The figure-eight stellarator uses one set of magnetic coils and the twist of the vacuum vessel to create the appropriate magnetic field. (c) In the classical stellarator, the total magnetic field is created by a set of toroidal coils and a set of helical coils with current flowing in opposite directions. (d) The torsatron uses a single set of helical windings to provide the toroidal and poloidal magnetic fields. Generally, an additional set of toroidal coils (not shown in the sketch) is necessary to provide an additional vertical field. The standard heliotron configuration is similar to that of the torsatron but has an additional set of toroidal coils.

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The tokamak and stellarator (figure 8) contain the plasma in a toroidal, or doughnut-shaped, vacuum chamber. The heliotron is a variation of the standard stellarator configuration. In its present state, the tokamak is a pulsed device because the plasma current is driven by a transformer action based on changing magnetic fields.

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Figure 9
Magnetic Mirror Devices



(a) In "simple" magnetic mirror devices, solenoidal magnets confine the plasma radially and high-field magnetic choke coils reflect the axially escaping nuclei back into the central region. (b) Tandem magnetic mirror devices employ special endplug magnets to reduce the axial outflow of nuclei that occurs in simple magnetic mirror devices.

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In magnetic mirror devices (figure 9), the plasma is contained in a cylindrical vacuum chamber. Tandem mirror concepts with complex endplugs (a simple version is shown in figure 9) have been developed to prevent excessive leakage of plasma out the ends of the cylinder. Currently, tandem mirrors are the most developed of the nontokamak MCF devices.

Inertial confinement fusion (ICF) uses high-energy laser or particle beams to compress very small pellets containing deuterium and tritium (figure 6). The inward moving mass (or inertia) of the pellet delays the explosion of the hot, dense, fusion plasma formed at the core until a large number of fusion reactions have occurred. Most laser fusion systems use glass or CO₂ lasers. Although some characteristics of glass

lasers make them very good experimental tools, their efficiency is too low for them to be used in a fusion reactor. On the other hand, some characteristics of the CO₂ laser are suitable for a reactor but its long-wavelength light does not couple efficiently to fusion pellets. A special type of pellet will have to be developed before CO₂ lasers can be used in fusion reactors. Although particle-beam fusion appears to have promise, it is much less developed than laser fusion.

The two primary milestones in an experimental fusion program are the demonstration of scientific feasibility and of engineering feasibility. Scientific feasibility is defined as the point at which the fusion energy produced in the plasma is equal to the energy put into the plasma to make the fusion reactions occur. Engineering feasibility takes into account all the inefficiencies of the total fusion system and is defined as the point at which the fusion energy produced in the plasma is equal to the total energy put into the fusion system. It is quite possible that scientific feasibility will be demonstrated during the late 1980s.

The transition from an experimental fusion program to a fusion power program will probably be accomplished by the construction of a prototype power reactor and then a demonstration power reactor. The prototype reactor will be a net energy producer and will demonstrate most reactor-relevant technologies. The demonstration reactor will be engineered so that it will provide reliable data on the economic aspects of a power reactor.

An MCF power reactor will probably use superconducting magnets to reduce power requirements. Such a reactor also will need auxiliary heating devices to create and maintain the high temperature of the plasma. Currently, neutral beam sources are the most used auxiliary heating technique. Because of the complexity and high-power consumption of these sources, radiofrequency generators are being developed as replacements for neutral beam sources.

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In a pure fusion power reactor using deuterium-tritium fuel, the heat from the fusion reaction is given off in the form of neutron energy. This heat can be used to produce steam for driving generators in the same way as is done in normal electrical power plants. In addition, the absorption of neutrons in a lithium coolant produces tritium for future use in fusion reactions.

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In the fusion-fission hybrid reactor concept, a fusion reactor is surrounded by a blanket of fertile material (that is, material that can be converted into fissile material by the absorption of neutrons). The fusion neutrons are used to breed fissile material in the blanket. A hybrid reactor could use a less sophisticated fusion system than would a pure fusion power reactor. The addition of a fertile blanket around the fusion system, however, seriously increases the complexity of the hybrid reactor. Although some studies have been done on the design and safety of hybrid reactors for power production and for reactor fuel production, little research has been done on the structure and integration of the blanket system.

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